Fully symmetric nulling beam combiners

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A simple method of nulling broadband light is presented. A mirror-symmetric pair of right-angle periscopes is first used to introduce a geometric field flip between two incident light beams, after which the light is combined by means of one of a number of constructive two-beam interferometers. A reciprocal pair of beam-splitter passages provides for complete symmetry. Such an approach greatly eases beam-splitter design requirements and should find use both in initial ground-based nulling experiments and ultimately in space-borne interferometers targeted at direct extrasolar planet detection.

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1. Introduction

The technique of nulling interferometry has the potential to attenuate the light from nearby stars sufficiently to enable the direct detection of terrestrial planets in orbit around them.[1] Various methods have been proposed for achieving the necessary deep and stable starlight cancellation. Candidate nulling architectures include approaches based on rotational shearing interferometry,[2] field inversion upon passage through focus,[3] and dispersive phase retardation,[4] all of which can be classified as exotic interferometers. To date, only the approach based on a fiber-coupled rotational shearing interferometer has successfully demonstrated the deep and stable nulling of broadband light.[2] Here we describe a family of alternative nulling approaches that has the virtues of simplicity (all flat optics) and complete symmetry, thus greatly easing several design constraints.

The near-perfect subtraction of the fields incident on two telescopes viewing a common source (e.g., a star or galactic nucleus) calls for a high degree of symmetry in the two optical beam trains and in the beam combiner. However, each of the nulling approaches proposed to date retains a certain degree of asymmetry. In particular, in single-pass beam-splitter configurations, the beam-splitter reflection and transmission coefficients may be unequal. In the through-focus approach, the incidence angles on the secondary mirrors of the retroreflector assemblies will differ. In all cases, unbalanced traversals of antireflection coatings in the beam-splitter–compensator pair may be present. Finally, common to all approaches, differences in the complex reflection coefficients for the two polarization states, and across the passband, may exist. Since each of these asymmetries limits the maximum broadband stellar rejection ratio attainable, an alternative nulling approach that eliminates or minimizes such asymmetries would be advantageous.

The impetus for the new design presented here was the idea that it should be possible to separate the field-flip and the beam combination stages. If a relative field reversal were introduced first, subsequent superposition of the two input beams in a standard interferometer would yield field subtraction rather than addition at zero optical path difference (OPD), allowing standard interferometric beam combiners to be employed. In addition, if the optical design could be made completely symmetric, it would theoretically be possible to subtract two identical input beams perfectly (neglecting real-world limitations such as alignment and phasing errors, and coating variations).

2. Field-Flip Stage

A simple method of providing a relative field reversal between two parallel, collimated beams is illustrated in Fig. 1: A pair of mirror-symmetric right-angle periscopes yields a relative 180° rotation of both the input fields and the apertures. Because the two mirrors in each periscope also reverse the role of s and p-plane reflections, the two incident polarization states are affected symmetrically by the mirror pair, with one s-plane and one p-plane reflection per periscope for each incident polarization. Thus, as long

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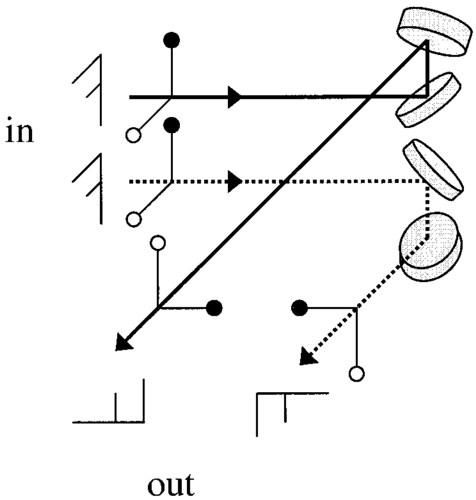

Fig. 1. Illustration of a mirror-reflected pair of right-angle periscopes. Each beam encounters two mirrors at the locations of the 90° folds. Both the apertures and the fields undergo a relative rotation of 180° because of the oppositely directed middle beam segments. Each polarization component undergoes one s- and one p-plane reflection.

as the mirror coatings are identical, no s–p phase delay will be incurred. After passage through these periscopes, the outgoing fields will thus be identical to the input fields, except for a relative field reversal. Since in most implementations of astronomical interferometers a pair of fold mirrors would be used to send the two incoming beams into the beam combiner, such a pair of right-angle periscopes actually adds only one mirror reflection per beam train.

3. Beam Combiner

With a relative field flip already in place, a constructive beam combiner should provide the required achromatic null. Considering first the single-pass beam-splitter case, perfect cancellation requires that the transmitted and the reflected beams have equal intensities so that $|r| = |t'|$, or equivalently, $|r'| = |t|$, must apply, where r, t and r', t' are the beam splitter's complex reflection and transmission coefficients for radiation arriving from opposite directions [Fig. 2(a)]. However, in practice these coefficients can differ significantly, especially if dual-polarization operation is demanded. We therefore turn to the case of double-pass beam splitters, where the beam-splitter performance requirements are significantly eased.

The most familiar double-pass case, a laboratory Michelson interferometer [Fig. 2(b)], has one output on either side of the central beam splitter. Each output is the superposition of two contributions. One output (hereafter the balanced output) consists of the superposition of two terms proportional to the coefficient cross products rt and tr', whereas the second output (the unbalanced output) has two contributions proportional to the squares of the individual coefficients, r^2 and tt'. As in the previous case, r^2 and tt' are not necessarily equal. However, rt and tr' are balanced to first order, because generally $r \approx r'$. In a standard single-input Michelson interferometer the balanced output normally experiences constructive interference at zero OPD, because the two contributions arrive in phase, so such an output is not useful for nulling. In contrast, in a rotational shearing interferometer (i.e., a Michelson interferom-

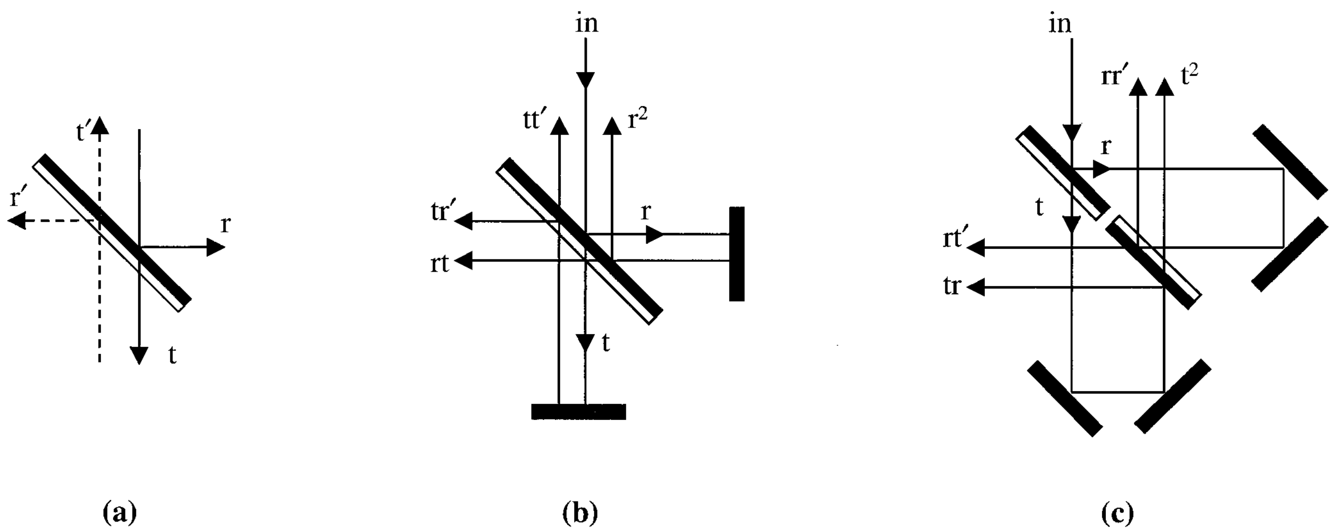

Fig. 2. (a) Definition of beam-splitter electric field reflection and transmission coefficients. The beam splitter is illustrated as composed of a substrate (clear) with a multilayer dielectric coating (black) on one side. The opposite side of the substrate has an antireflection coating that is not shown. (b) Illustration of the electric fields arriving at the outputs of a Michelson interferometer, in which the beam splitter is used in double pass. At zero OPD, the light emerges in the constructive balanced outputs given by the coefficient cross products. In the figure the outputs are offset for clarity. This layout applies as well to rotational shearing interferometers, in which the balanced outputs are made destructive at zero OPD by replacing the two flat mirrors in the two arms with a pair of orthogonal rooftop mirrors. (c) Illustration of the electric fields arriving at the outputs of a modified interferometer in which an inverted pair of beam splitters is used for the two beam-splitter encounters.

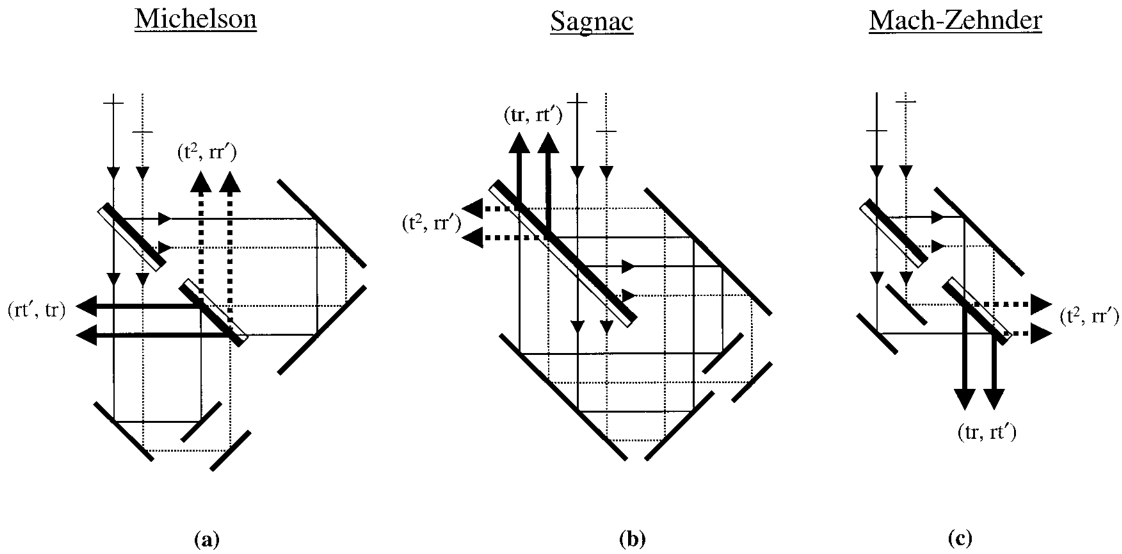

Fig. 3. Three configurations for constructive beam combiners derived from classical Michelson, Sagnac, and Mach–Zehnder interferometers. At zero OPD, constructive interference occurs at the balanced outputs (shown as solid heavy arrows). In conjunction with a prior field flip these balanced outputs become nulled outputs at zero OPD. The offset pairs of short segments on the input beams indicate the wave-front offsets needed for path-length matching at the outputs.

eter with its two flat end mirrors replaced by two orthogonal rooftop reflectors), the cross terms remain the same, but a relative field flip internal to the interferometer introduces a relative phase shift of π radians, and thus the cross terms at the balanced output subtract. Exactly the same state of affairs would occur for a normal Michelson interferometer if a prior field flip were introduced.

Before we consider how to generalize to two input beams, one further point needs to be addressed. The difference term present at the balanced outputs, $t(r - r')$, is not necessarily exactly equal to zero, because $r - r' \neq 0$ if losses are present in the beam splitter.[5,6] However, if the beam splitter were to be inverted for the second beam-splitter passage [as in Fig. 2(c)], the contributions to the balanced outputs for equal inputs become instead rt' and tr, with a difference of $r(t' - t)$. As a consequence of the right-and-left incidence theorem,[5,6] the reciprocal transmission coefficients, t and t', of a multilayer system embedded in a lossless dielectric medium must be equal even in the presence of internal absorption. As a result, $r(t' - t)$ is identically zero, independent of the specific properties of either the beam splitter or the incident field, such as the beam splitter's r and t coefficients, and the wavelength, polarization state, and angle of incidence of the radiation. Thus a perfectly nulled output is theoretically possible with such a reciprocal beam-splitter pair, even for broadband dual-polarization light. A reciprocal beam-splitter pair arranged as in Fig. 2(c), with the input beam first hitting the beam-splitter side of the substrate, also minimizes (at one each) the number of passages through the substrate and the rear-surface antireflection coating.

Although use of a reciprocal beam-splitter arrangement could further improve the performance of the rotational shearing interferometer used in the nulling experiments to date at the Jet Propulsion Laboratory,[2,7] we return instead to the idea of using a normal constructive interferometer to null a pair of already reversed electric fields. Use of a pair of beam splitters immediately suggests a Mach–Zehnder configuration,[8] but any of the typical constructive interferometer configurations, e.g., Michelson, or Sagnac,[8] can also serve as a starting point. However, these familiar interferometers are normally used as single-input devices, so some rearrangement of the optical paths is necessary to use them as beam combiners.

Simple arrangements for dual-input Michelson-like, Sagnac-like, and Mach–Zehnder-like interferometric beam combiners are given in Fig. 3. A similar Mach–Zehnder-like arrangement has already been suggested for use as a three-way constructive beam combiner.[9] In all the arrangements in Fig. 3, the second beam-splitter encounter is reciprocal to the first (in the Sagnac-like system, this is effected passively by going around the beam splitter) so that the nullers are perfectly symmetric with respect to both the beam-splitter encounters and the mirror reflections. The Mach–Zehnder-derived system is physically symmetric as well and has the fewest mirrors, and so has the simplest layout. The full layout for the Mach–Zehnder-derived case, including the right-angle periscopes, is shown in Fig. 4. Compared with the three-dimensional layout of the rooftop-based rotational shearing interferometer,[7] this new layout is significantly more symmetric and more compact and also has fewer reflections. It should thus show superior nulling performance, in addition to being easier to construct and align.

Finally, two subtleties merit mention. First, because of the right-angle periscopes, the entire layout cannot be planar. Although the postperiscope beam

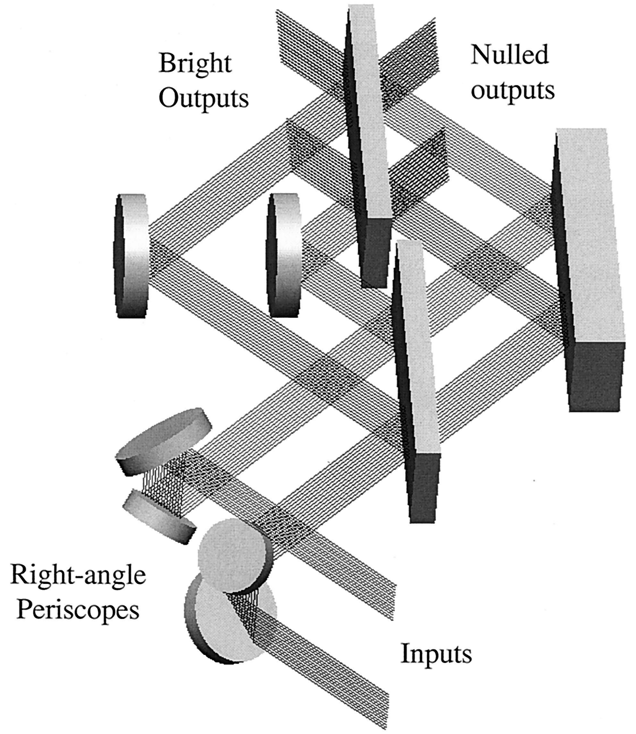

Fig. 4. Full layout of the Mach–Zehnder-derived nulling beam combiner, including the input mirror-reflected periscope pair. In this layout, the two input beams lie in a vertical plane, and the postperiscope nulling optics lie in a horizontal plane.

combiners are planar, the orientation of the beam-combiner plane is dependent on the periscope implementation and so may be rotated, by, e.g., 45° or 90°, relative to the plane of the input beams. Second, as Fig. 3 illustrates, path-length matching to the outputs requires the introduction of a path-length offset between the inputs. Without this external delay, a single lens cannot be used to illuminate both inputs for testing. This offset can be inserted upstream of the beam combiner by configuring or sizing the periscopes appropriately or by using the optical delay lines normally present in astronomical interferometers.

4. Conclusions

By separating the field reversal and beam combination functions, a simplified achromatic nuller design is obtained. The new design allows for rigorous symmetry of the optical train, accommodating losses and reflection/transmission asymmetries in the beam splitter as well as losses in mirror reflections. The simplified design provides a compact, mostly planar, nuller implementation based entirely on flat optics, with fewer reflections than previous designs. Because of its high degree of symmetry, this nuller design is inherently broadband and dual-polarization and so has the potential to outperform other designs.

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References

1. C. A. Beichman, N. J. Woolf, and C. A. Lindensmith, "The terrestrial planet finder (TPF): a NASA origins program to search for habitable planets," JPL Pub. 99-3 (Jet Propulsion Laboratory, Pasadena, Calif., 1999); http://tpf.jpl.nasa.gov.
2. K. Wallace, G. Hardy, and E. Serabyn, "Deep and stable interferometric nulling of broadband light with implications for observing planets around nearby stars," Nature **406,** 700–702 (2000).
3. P. Baudoz, J. Gay, and Y. Rabbia, "Interfero-coronagraphy: a tool for detection of faint companions," in Vol. 134 of the ASP Conference Series, *Brown Dwarfs and Extrasolar Planets*, R. Rebelo, E. L. Martin, and M. R. Zapatero Osorio, eds. (Astronomical Society of the Pacific, San Francisco, Calif., 1998), pp. 254–261.
4. R. M. Morgan, J. Burge, and N. Woolf, "Nulling interferometric beam combiner utilizing dielectric plates: experimental results in the visible broadband," in *Interferometry in Optical Astronomy*, P. J. Lena and A. Quirrenbach, eds., Proc. SPIE **4006,** 340–348 (2000).
5. P. Yeh, *Optical Waves in Layered Media* (Wiley, New York, 1988), Sect. 5.3.
6. Z. Knittl, *Optics of Thin Films* (Wiley, New York, 1976), Sect. 6.1.
7. E. Serabyn, J. K. Wallace, G. J. Hardy, E. G. H. Schmidtlin, and H. T. Nguyen, "Deep nulling of visible laser light," Appl. Opt. **38,** 7128–7132 (1999).
8. M. Born and E. Wolf, *Principles of Optics*, 6th ed. (Pergamon, New York, 1984).
9. D. Mozurkewich, "A hybrid design for a six way beam combiner," in *Amplitude and Intensity Spatial Interferometry II*, J. B. Breckinridge, ed., Proc. SPIE **2200,** 76–80 (1994).